

Tevatron Physics

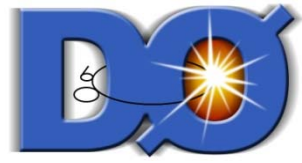
Fermilab Users Meeting

David Toback

Texas A&M University

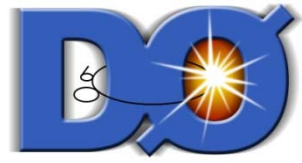
June 2014





Overview

- **The CDF and DZero collaborations are still doing exciting physics and publishing at a strong rate**
- **Focusing on legacy results that are competitive and complementary to the LHC**
- **In a phrase, our motto is “*get the papers out!*”**

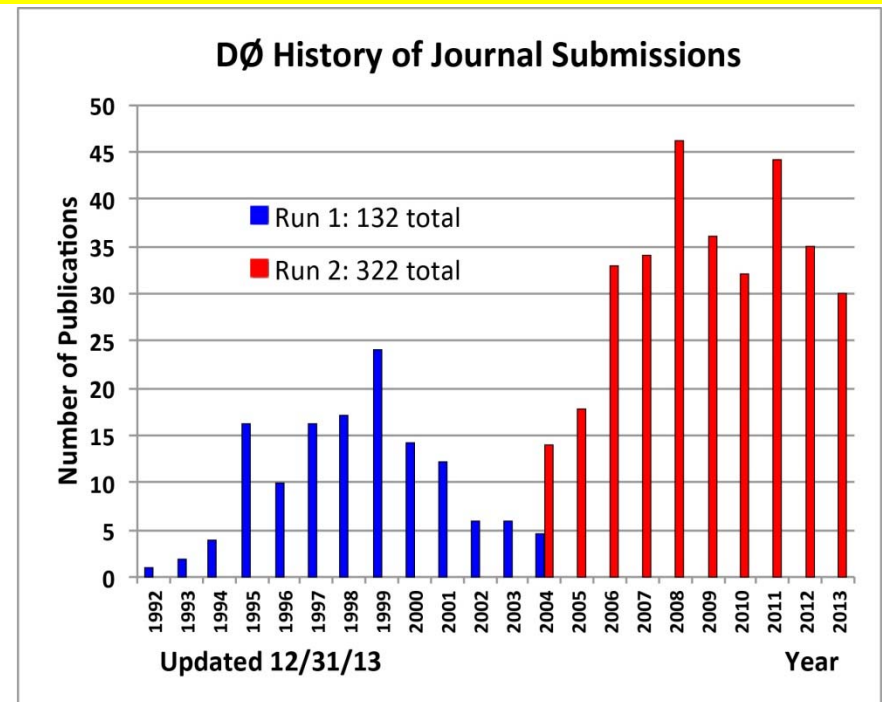
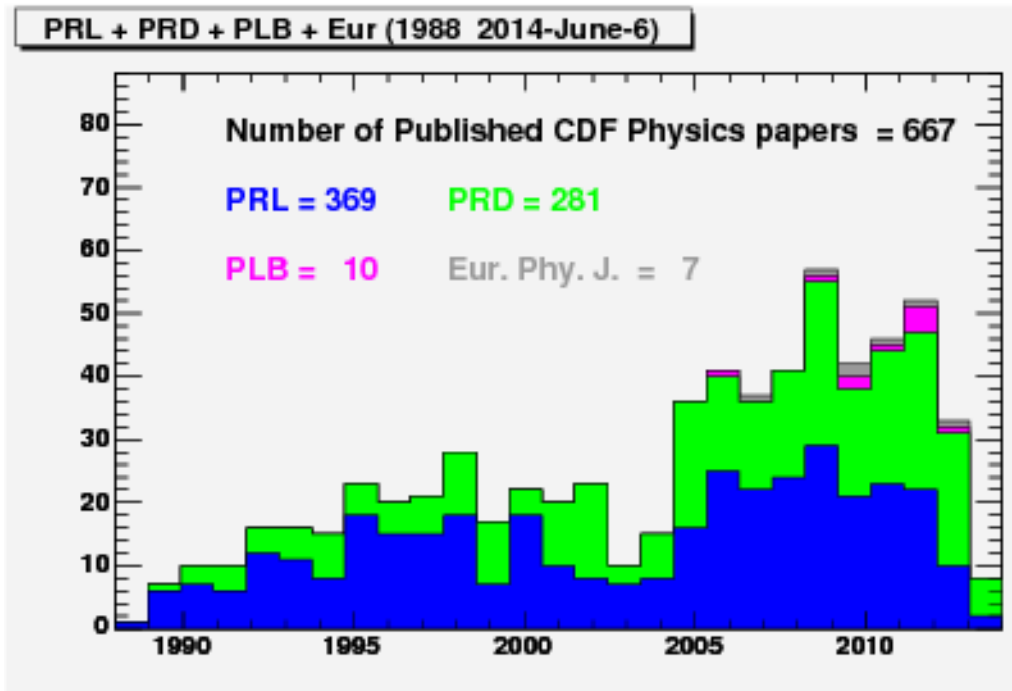


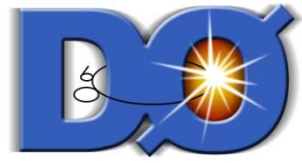
Publication History

CDF and DZero: ~30 paper each in 2013

Excellent results in all physics groups

Tevatron Legacy: Over 1,000 papers published and 1,000 PhD's granted





Rich Program

Selected Results

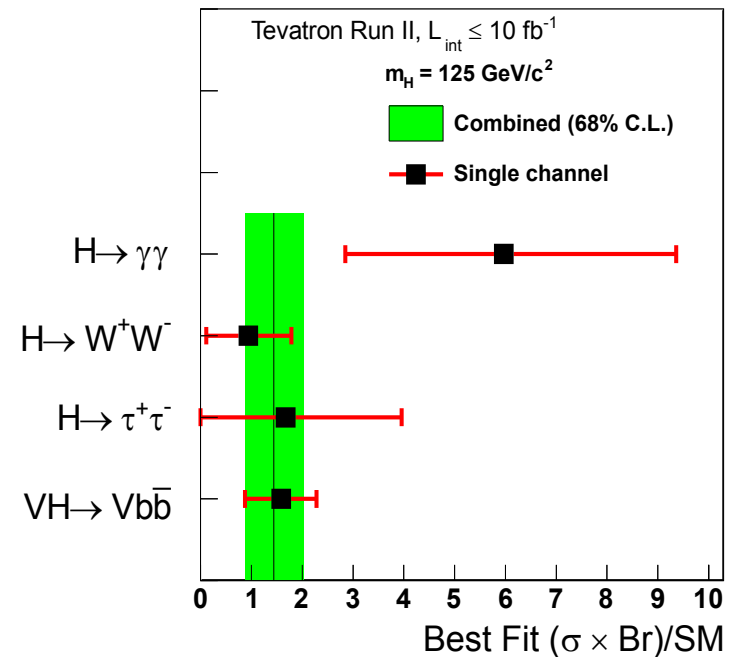
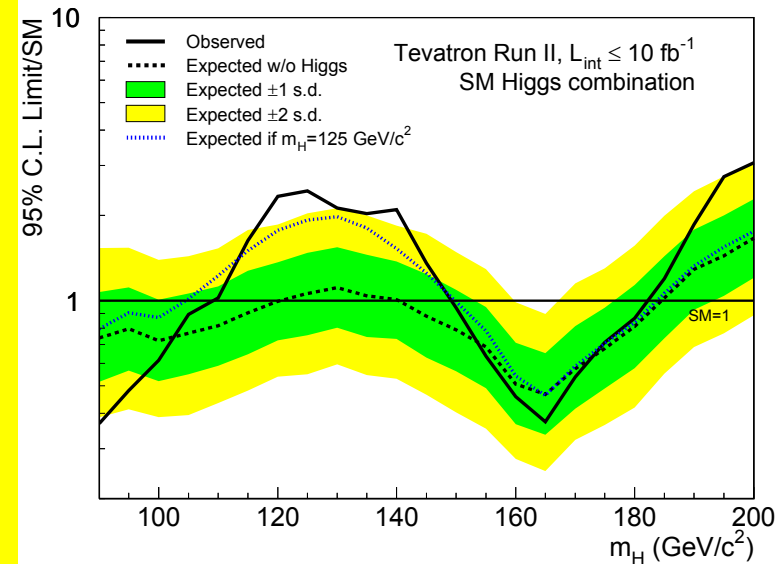
- **Higgs**
 - Final Higgs Combination
 - Higgs Couplings
- **Exotics/New Phenomena**
 - Search for Heavy Vector Bosons
- **QCD**
 - Exclusive production
 - Double parton Interactions
 - W/Z + Jets
 - Vector Boson +HF
- **Heavy Flavor**
 - CP Violation B^\pm decays
 - Excited B-mesons
 - b -Baryon properties
 - Di-muon charge asymmetry
- **EWK**
 - A_{FB} : $\sin^2\theta_{eff}$ and M_W
 - WW and ZZ Results
 - W Mass
- **Top**
 - Top Pair-Production Cross section
 - Top Mass
 - Single Top s+t
 - Single Top in s-only
 - A_{FB} in tt
 - A_{FB} in bb



Final Higgs Combination



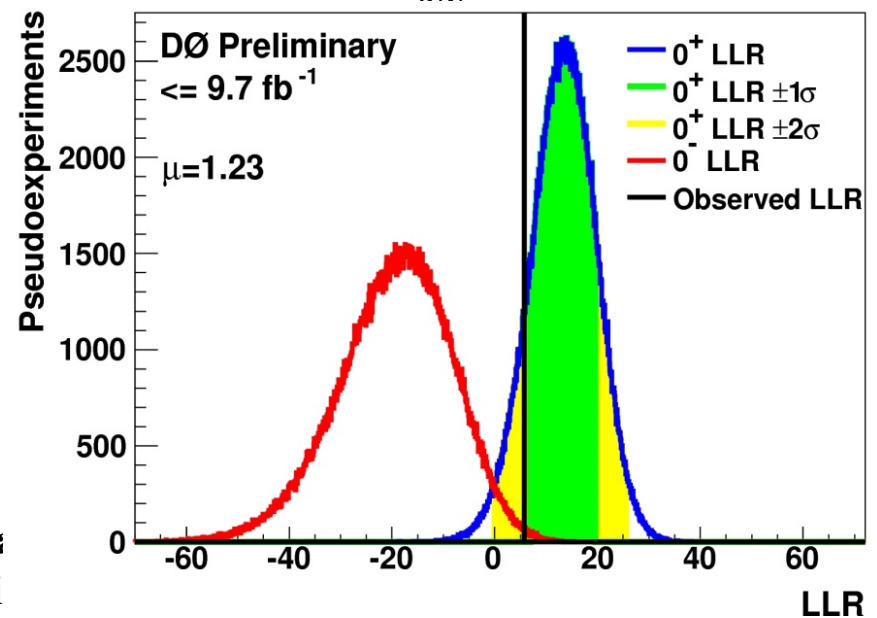
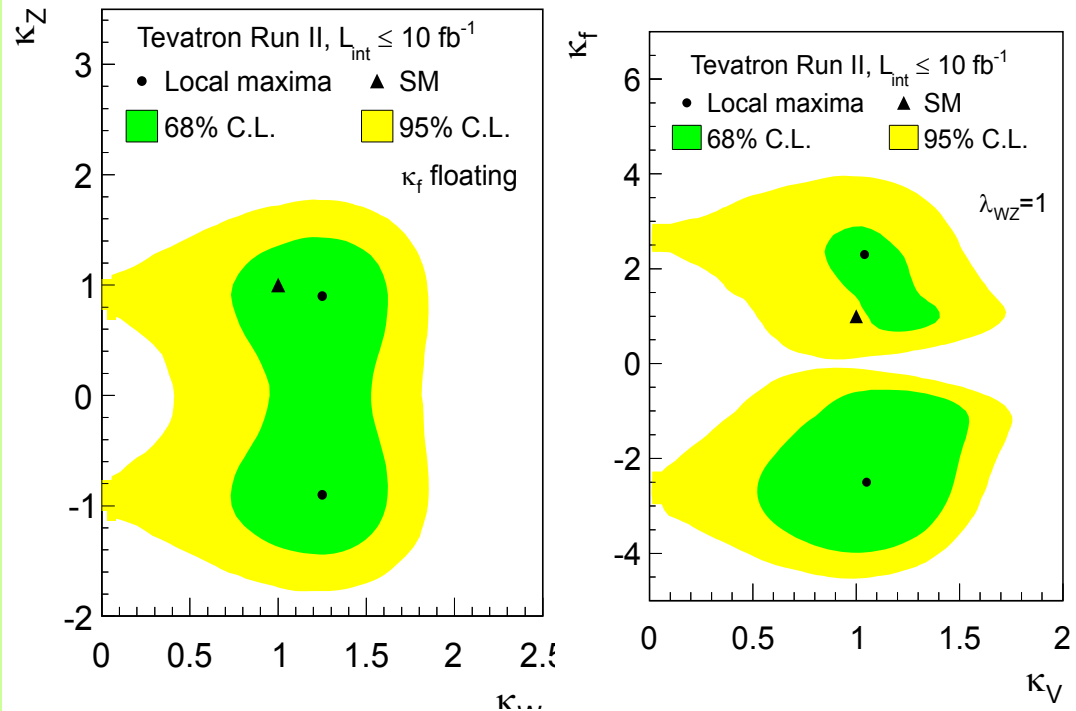
- The Higgs groups at both CDF and DZero have completed their search work
- Powerful results in bb are complementary to the final states from the LHC
- Observed significance is 3.0σ at a Higgs mass of 125 GeV
- Tevatron combination published
 - PRD 88, 052014 (2013)





Higgs Couplings

- **The world-wide emphasis has shifted to property measurements**
- **Combination of CDF and DZero results on Higgs Spin-parity is in progress**
 - **DZero results are public (Conf Notes 6387 and 6404)**
 - **CDF results are nearing completion**
- **All results are currently consistent with the SM**



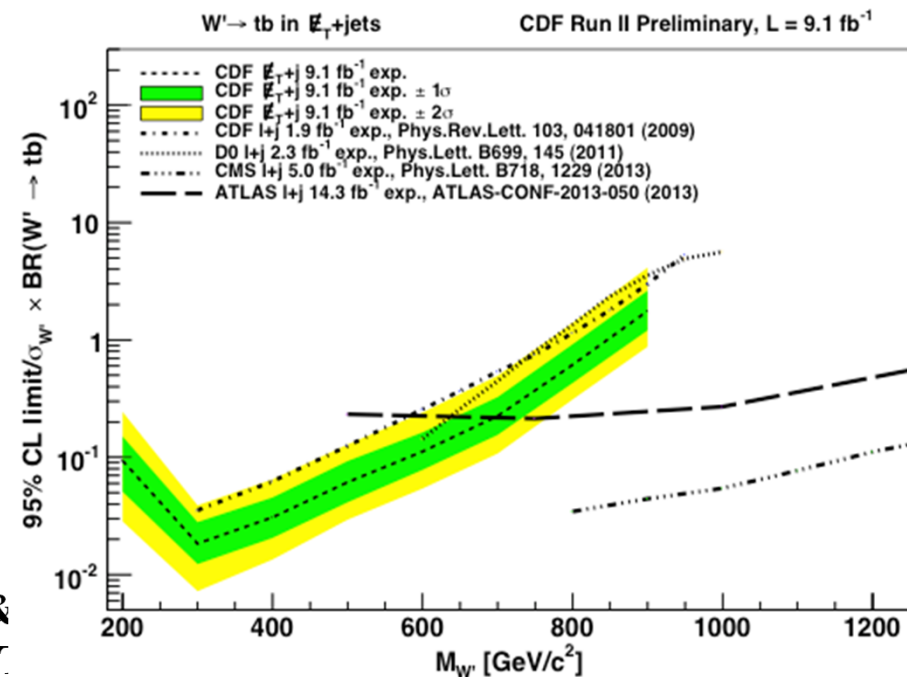
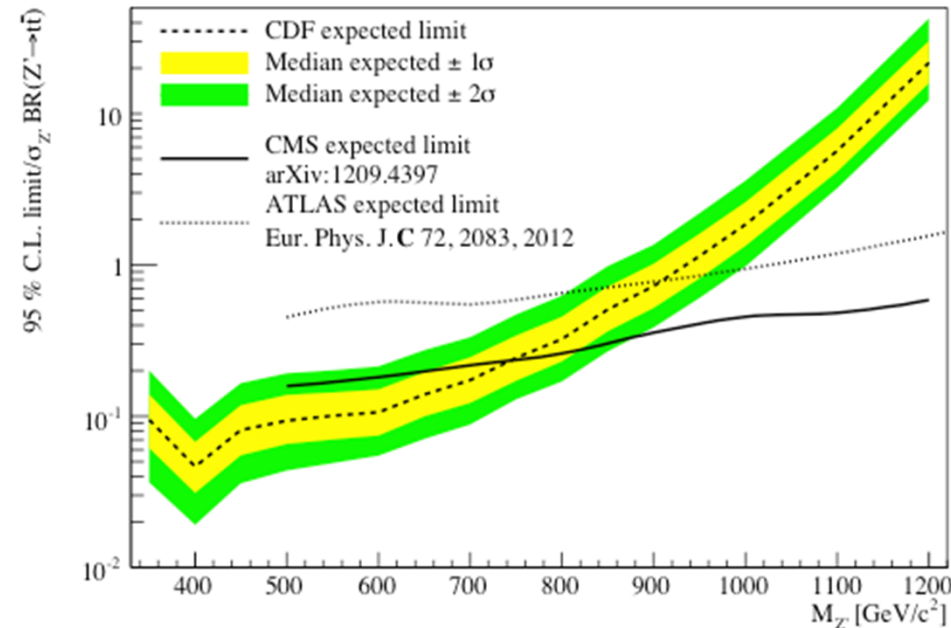


Search for Heavy Vector Bosons

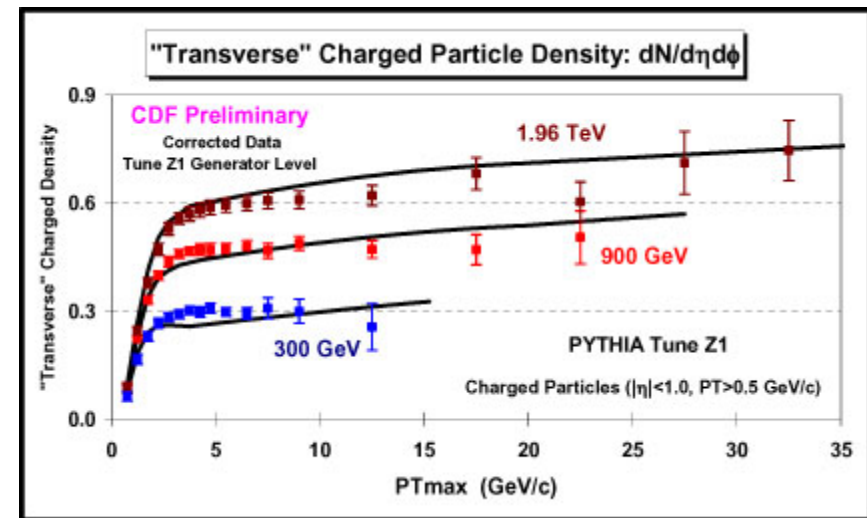
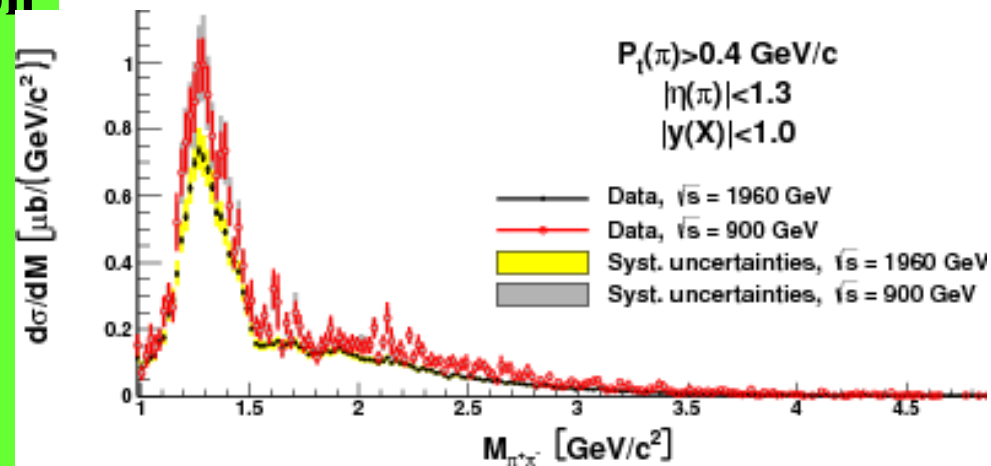
Exotics/New Phenomena



- While the Tevatron isn't competitive for the high mass searches any more, there are still a number of places where it has advantages
 - PPbar vs. PP
 - Low number of interactions per crossing
- New limits on $W' \rightarrow tb$ and $Z' \rightarrow tt$ are the world's best at intermediate masses
 - PRL 110, 121802 (2013)
 - CDF Public note 11079
- A few more results to come in the next year
 - Delayed photons
 - Monopoles
 - Others



- Measurements of Exclusive Production are important in their own right as well as for input in our Monte Carlos (Pythia, Herwig++ etc.)
- **Central Exclusive Hadron Pair Production**
 - CDF Public Note 10841
- **Many other exclusive results**
 - High mass di-jet production
 - Exclusive di-jet production,
 - exclusive di-photon
 - exclusive χ_c production
- **Measurements at multiple Tevatron energies**
 - 300, 900 and 1960 GeV
 - CDF Pub Note 10841 and 10874

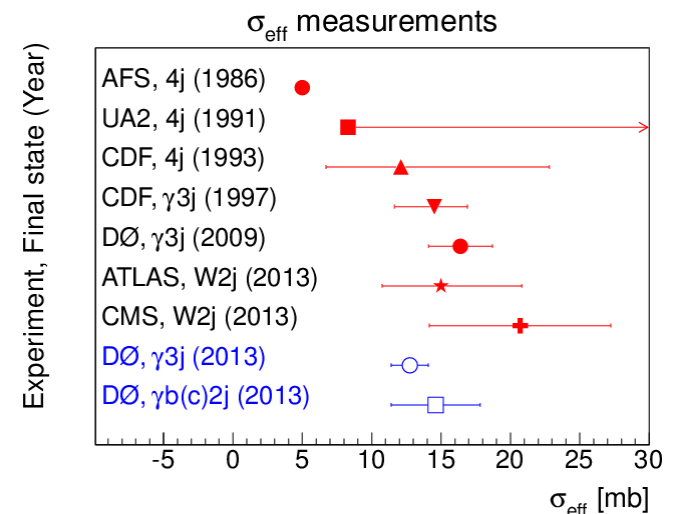
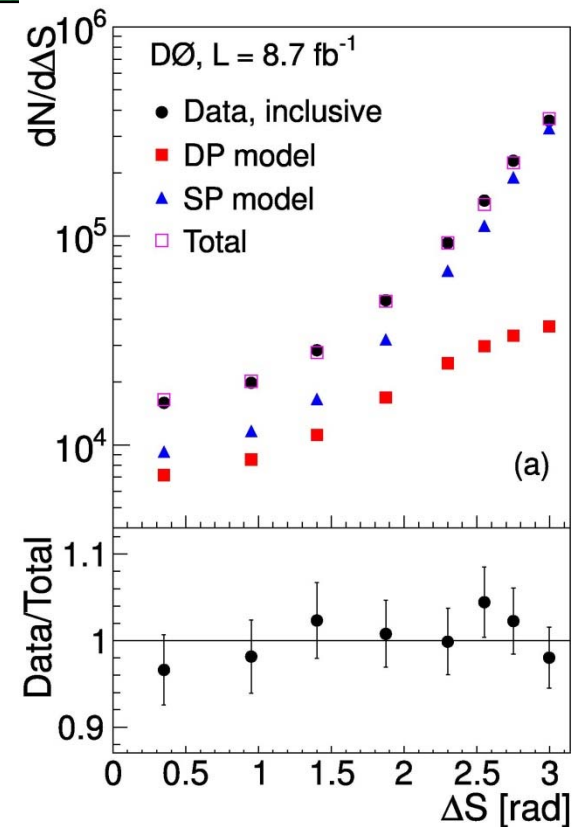




Double Parton Interactions



- Ability to separate single and double parton interactions
- Measurements in both $\gamma + 3$ jets and $\gamma + b/c + 2$ jets events
 - DZero: PRD 89, 072006 (2014)
- In agreement with the SM





W/Z+Jets

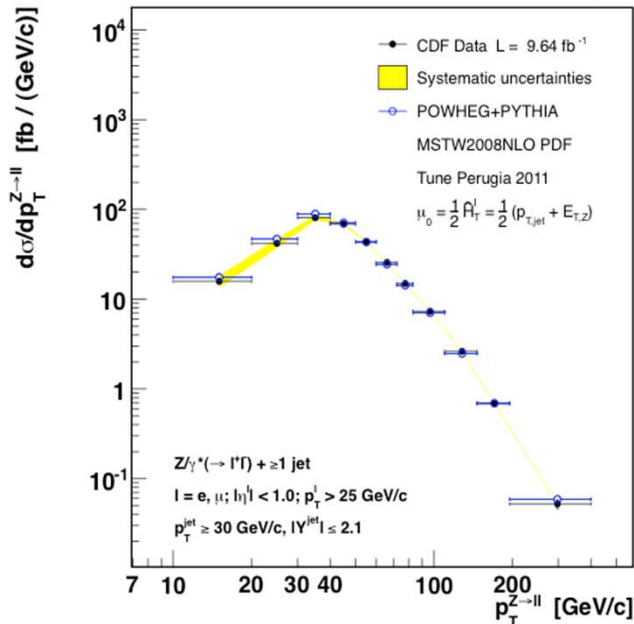


Z+jets & W+jets Cross Section Measurements

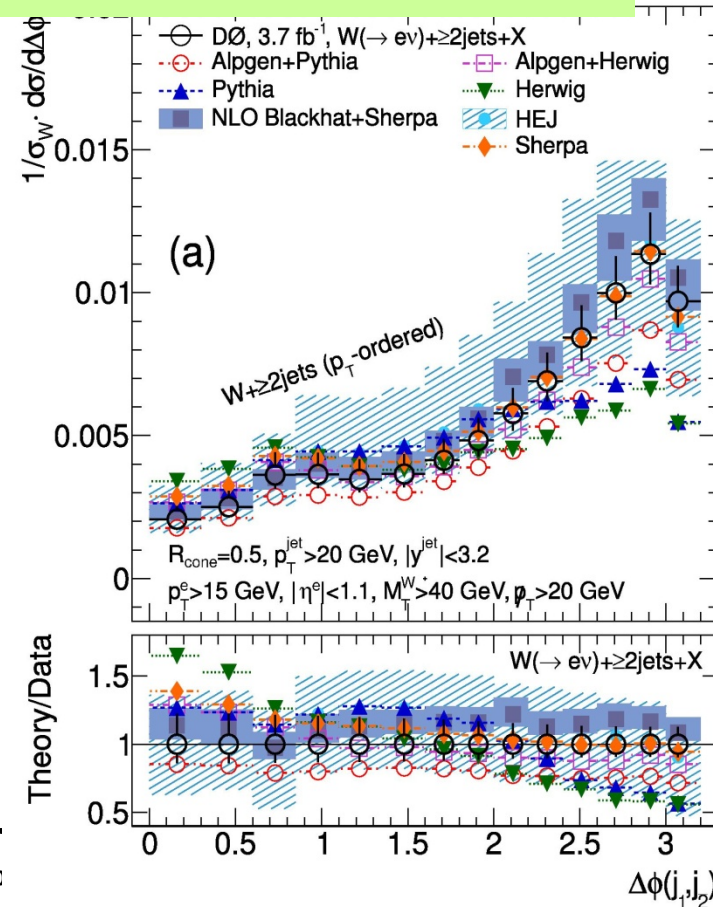
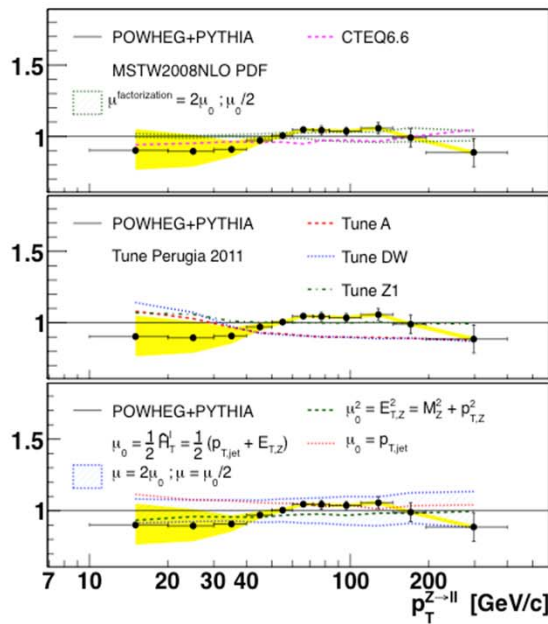
CDF: Public Note 10216

DZero: PRD 88, 092001 (2013)

CDF Run II Preliminary



Data / Theory



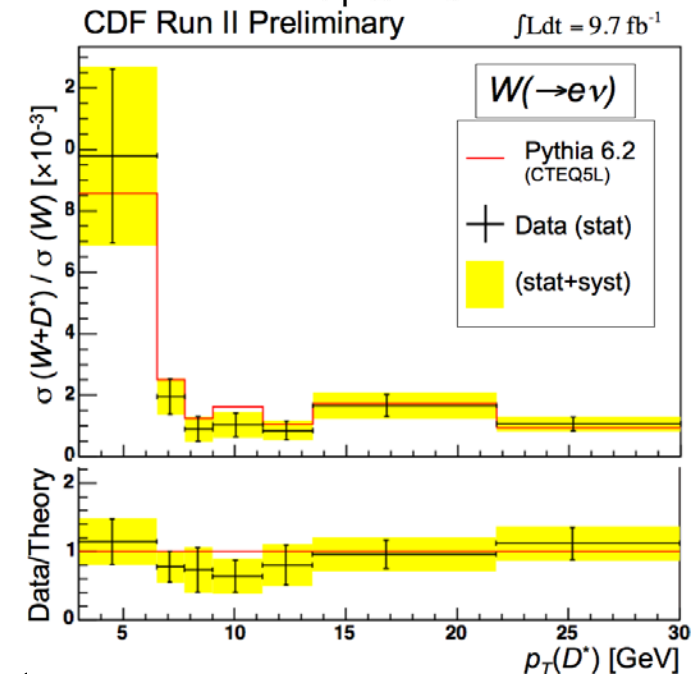
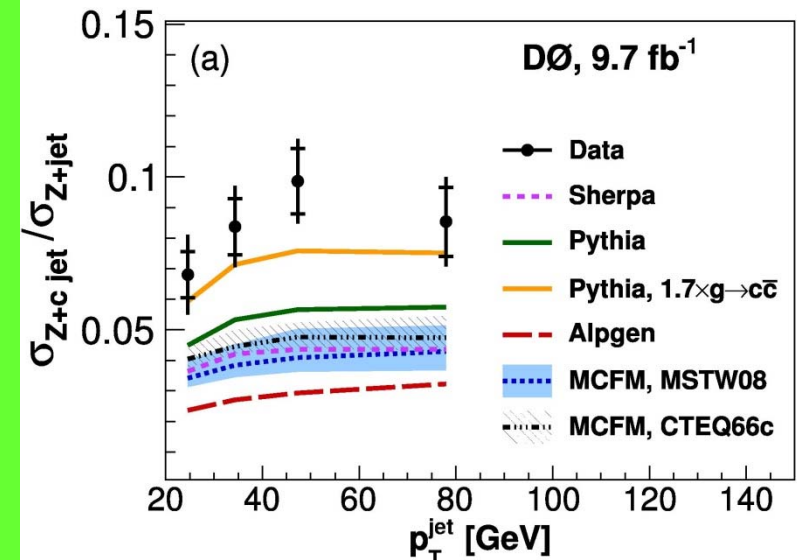
QCD@NLO works reasonably well
and is very useful for model builders

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Vector Boson + HF

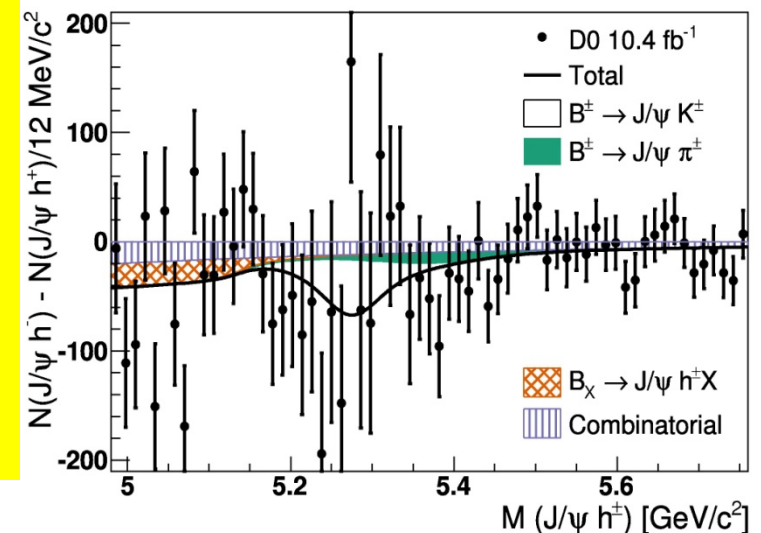
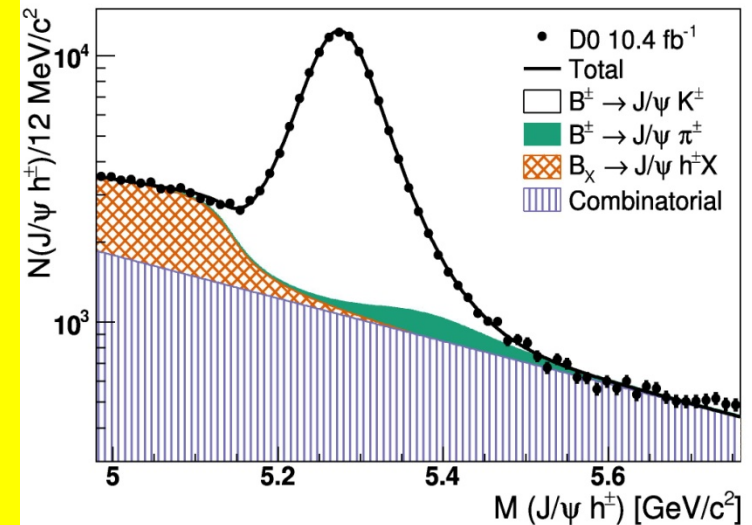
- Using the low pileup environment to pushing down to low rate and/or soft production
- **V+Charm jet**
 - DZero: PRL 112, 042001 (2014)
- **V+D***
 - New method allows for lower P_T Charm
 - CDF Public Note 11087
- **W/Z+Upsilon**
 - No observation, new limits
 - CDF Public Note 11099

	$\Upsilon + W$	$\Upsilon + Z$
expected limit (pb)	5.5	13
observed limit (pb)	5.5	20



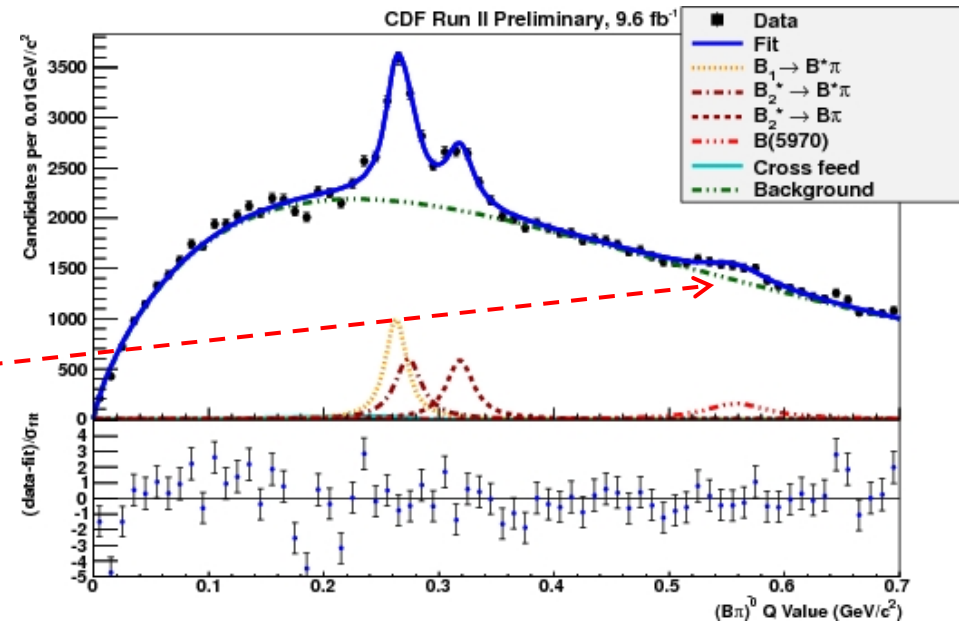
CP violation in B^\pm decays

- Analyzed decay multiple modes of B^\pm for CP violation
 - $B^\pm \rightarrow J/\psi K^\pm \rightarrow \mu^+ \mu^- K^\pm$
 - $B^\pm \rightarrow J/\psi \pi^\pm \rightarrow \mu^+ \mu^- \pi^\pm$
- World's most precise measurement
 - $A^{J/\psi K} = (0.59 \pm 0.36)\%$
 - $A^{J/\psi \pi} = (-4.2 \pm 4.8)\%$
- Consistent with SM expectations
 - DZero: PRL 110, 241801 (2013)



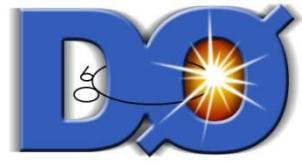
Excited B-mesons

- First evidence of resonances (4.4σ) consistent with two states of orbitally excited ($L=1$) B^+ -mesons
 - In both $B^0\pi^+$ and a $B^+\pi$ samples
- Measured masses and widths of all states, as well as the relative production rates
 - CDF: arXiv:1309.5961



Quantity	Value	Stat. uncert.	Syst. uncert.
MeV/c ²	MeV/c ²	MeV/c ²	MeV/c ²
$Q(B(5970)^0)$	558	5	12
$Q(B(5970)^+)$	541	5	3
$m(B(5970)^0)$	5978	5	12
$m(B(5970)^+)$	5961	5	3
$\Gamma(B(5970)^0)$	70	18	31
$\Gamma(B(5970)^+)$	60	20	40

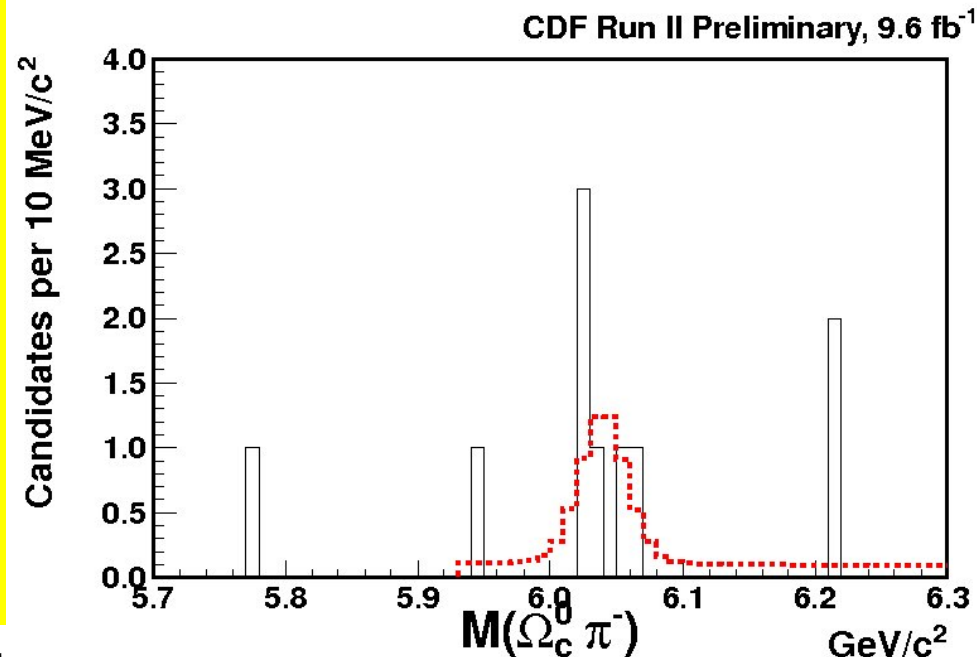
Masses are calculated assuming the state decays to $B\pi$.



b-Baryon Properties

- **Best measurements of the masses and lifetimes of Ξ_c and *b*-baryons**
- **First observations of $\Omega_b^- \rightarrow \Omega_c^0 \pi^-$ and $\Xi_b^0 \rightarrow \Xi_c^+ \pi^-$**
 - **CDF: PRD 89 072014 (2014)**
 - **Not yet seen at LHC**

Baryon	Mass (MeV/c ²)
Ξ_c^0	$2470.85 \pm 0.24 \pm 0.55$
Ξ_c^+	$2468.00 \pm 0.18 \pm 0.51$
Λ_b	$5620.15 \pm 0.31 \pm 0.47$
Ξ_b^-	$5793.4 \pm 1.8 \pm 0.7$
Ξ_b^0	$5788.7 \pm 4.3 \pm 1.4$
Ω_b^-	$6047.5 \pm 3.8 \pm 0.6$
$M(\Xi_c^0) - M(\Xi_c^+)$	$2.85 \pm 0.30 \pm 0.04$
$M(\Xi_b^-) - M(\Xi_b^0)$	$4.7 \pm 4.7 \pm 0.7$

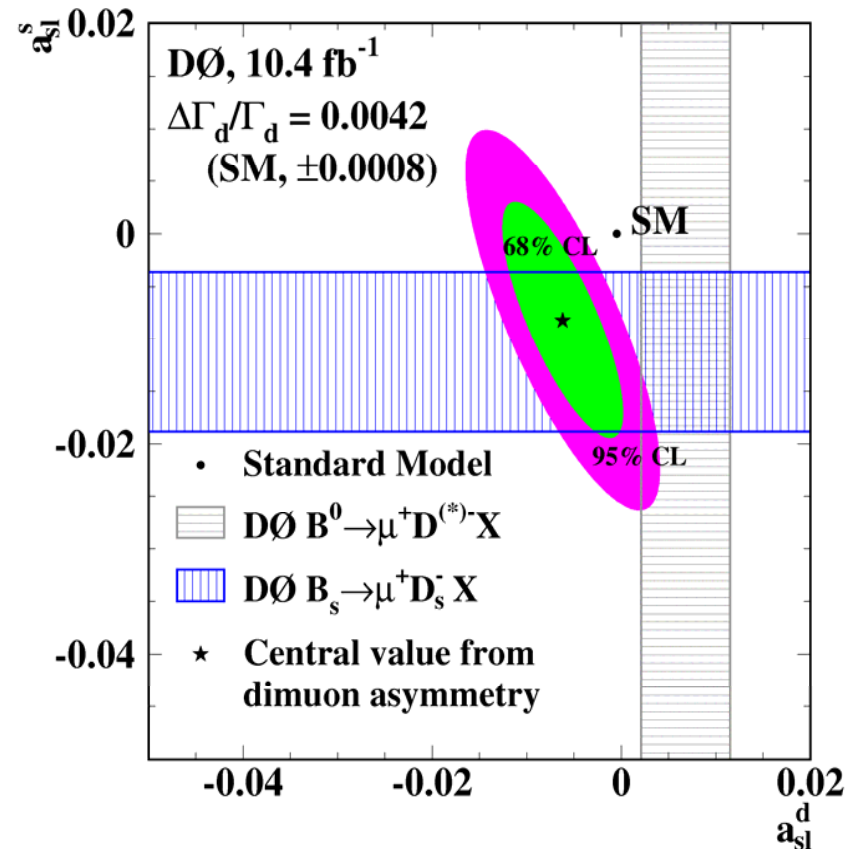




Like-sign di-muon charge asymmetry



- **Current result deviates from the SM prediction by 3.0σ**
 - **DZero: PRD 89, 012002 (2014)**
- **Result is consistent with independent DZero measurements**
 - **Semi-leptonic asymmetry in B^0 (a_{sl}^d): PRD 86, 072009 (2012)**
 - **Semi-leptonic asymmetry in B_s (a_{sl}^s): PRL 110, 011801 (2013)**
- **This effect is one of a few remaining puzzles from the Tevatron program which might indicate physics beyond standard model**

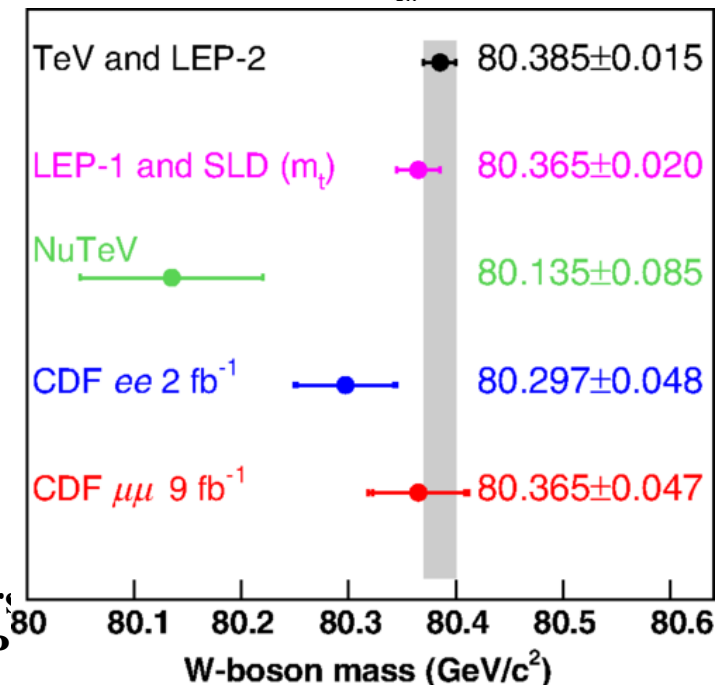
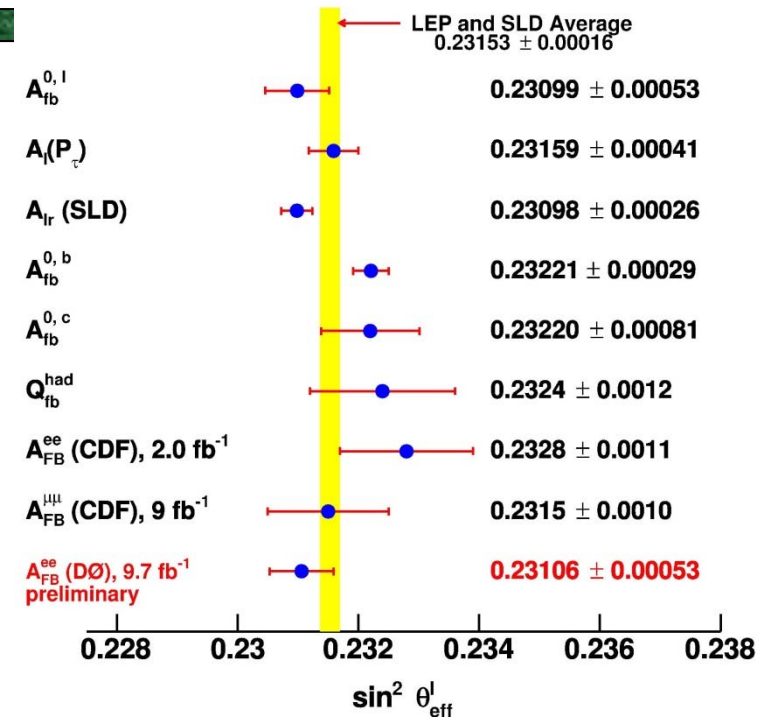


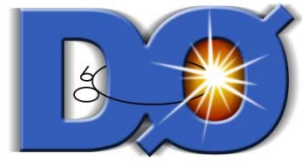


Precision EWK: A_{FB} from leptons $\sin^2\theta_{eff}$ and W -mass



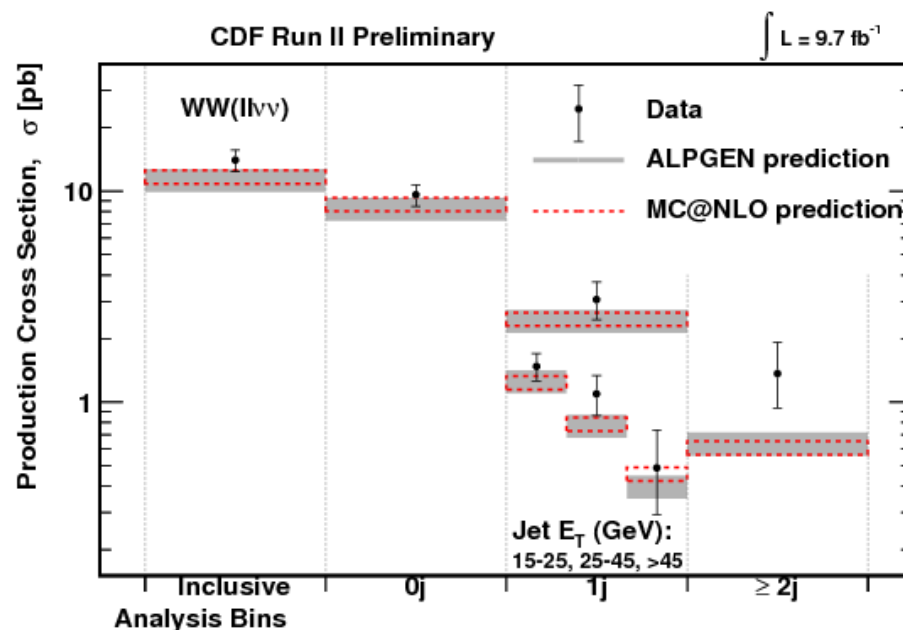
- A_{FB} from leptons provides a powerful way to measure $\sin^2\theta_{eff}$
- CDF:**
 - Interpret the results as an indirect W mass measurement \rightarrow quite competitive
 - New $\mu\mu$ measurement in PRD 89, 072005 (2014)
 - Result for ee in progress
- DZero:**
 - Single most precise $\sin^2\theta_{eff}$ measurement is in ee final state
 - Public Note 6426

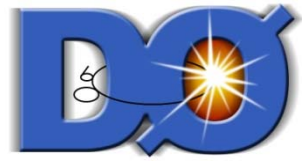




WW and ZZ Results

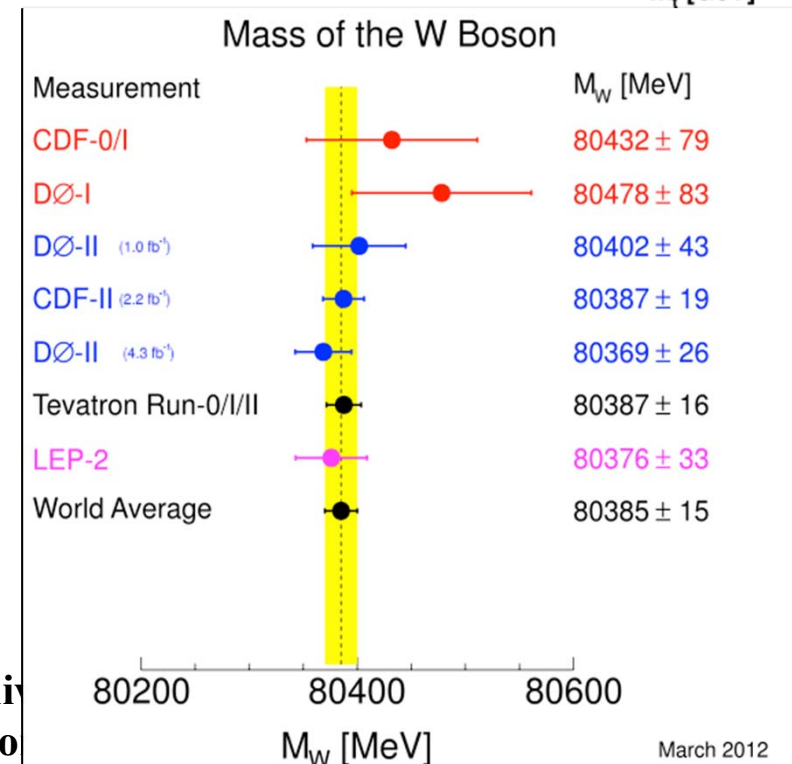
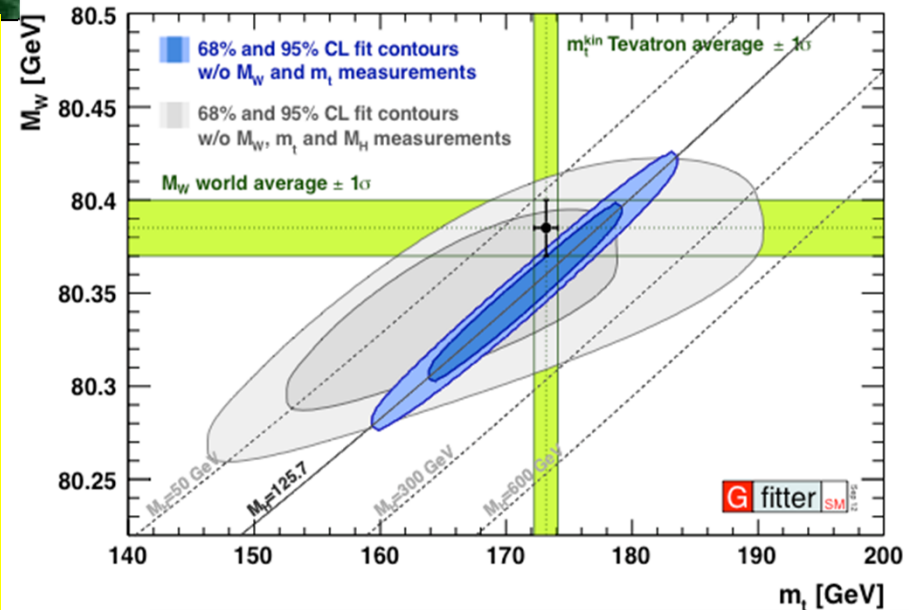
- **WW cross section**
 - New full data set results as a function of N_{jet} and Jet E_T
 - CDF Public note 11098
 - Dzero: PRD 88, 112005 (2012)
- **ZZ Cross Section**
 - $\sigma_{\text{ZZ}} = 1.04^{+0.32}_{-0.25}$ pb
 - CDF: PRD 89, 112001 (2014)
 - DZero: PRD 88, 0230080 (2013)
- **All in agreement with the SM**





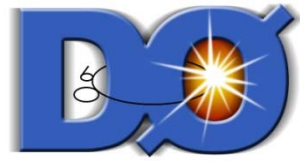
W Mass Measurement

- **Tevatron Combination**
 - PRD 88, 052018 (2013)
 - CDF: PRD 89, 072003 (2014)
 - DZero: PRD 89, 012005 (2014)
 - $M_W = (80387 \pm 16) \text{ MeV}/c^2$
 - **0.02% precision!**
- **Further reduction of uncertainties are difficult and time consuming**
 - Full-data results from both CDF and DZero in progress

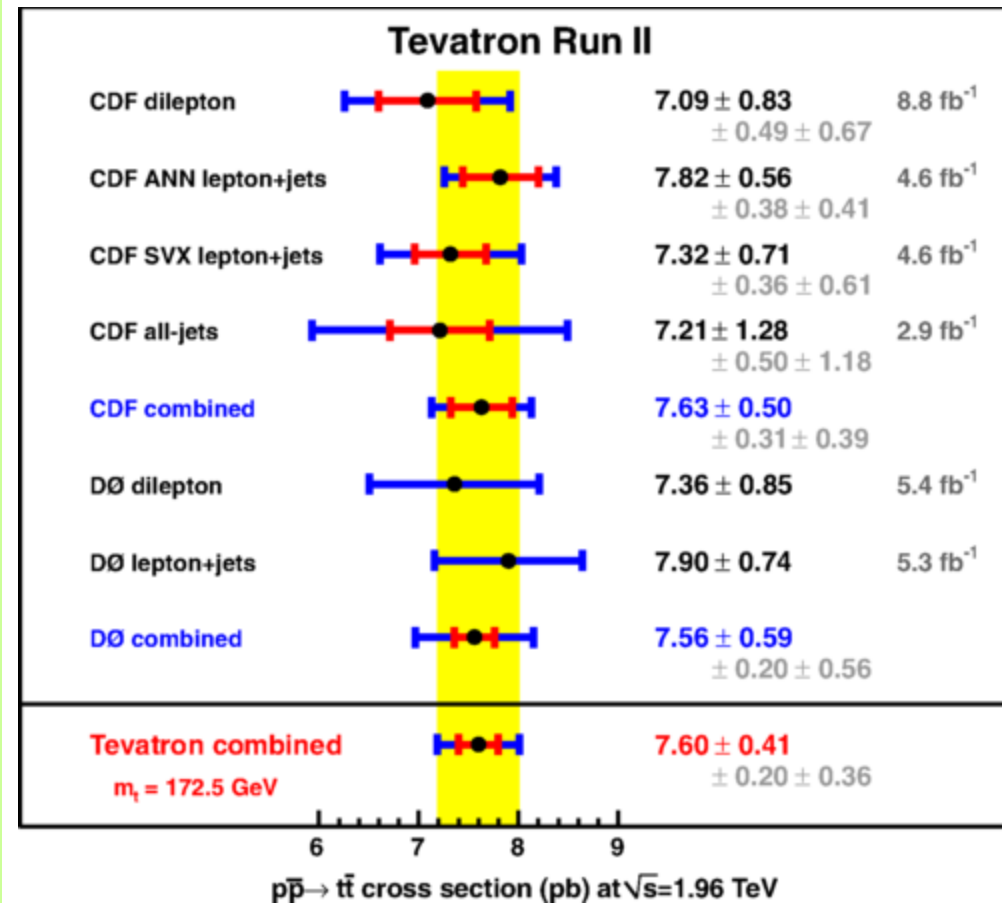




Top Pair-Production Cross Section



- **Combined CDF/DZero results from $\sim 8.8 \text{ fb}^{-1}$ published**
 - PRD 89, 072001 (2014)
- **Result is $7.60 \pm 0.41 \text{ pb}$**
- **CDF version in lep+jets with the full dataset nearing release**

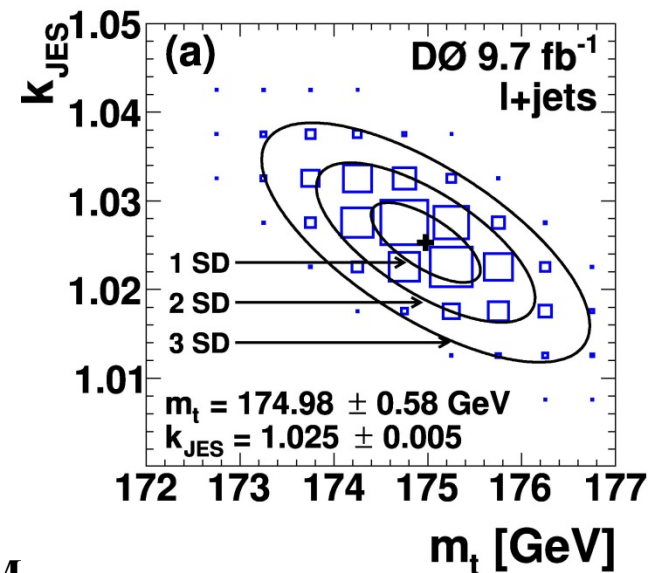
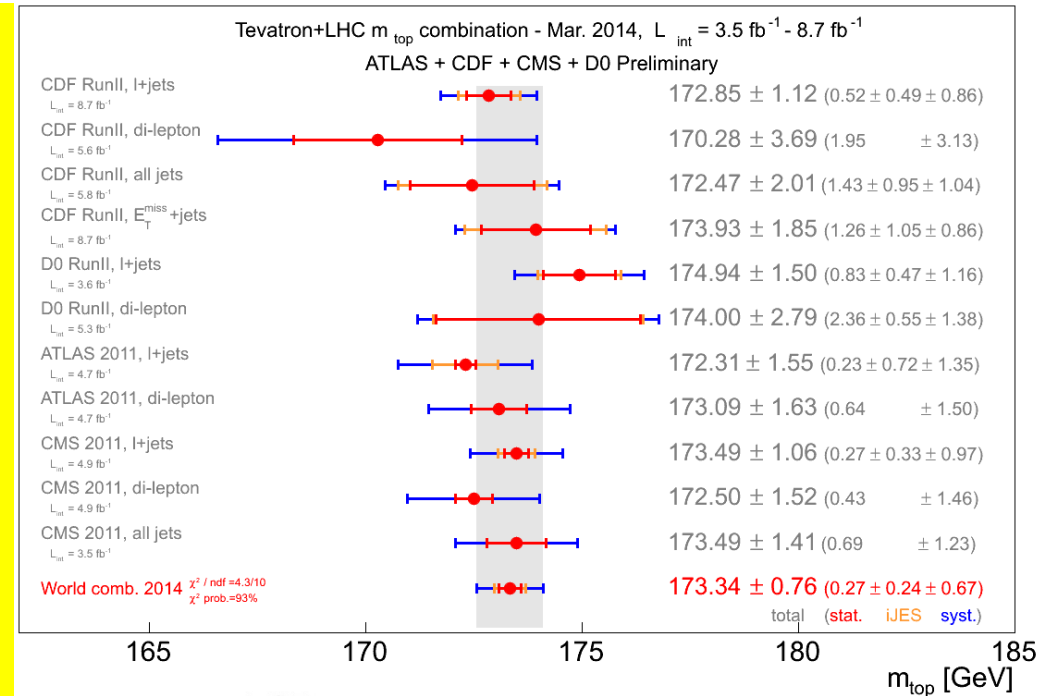




Top Mass



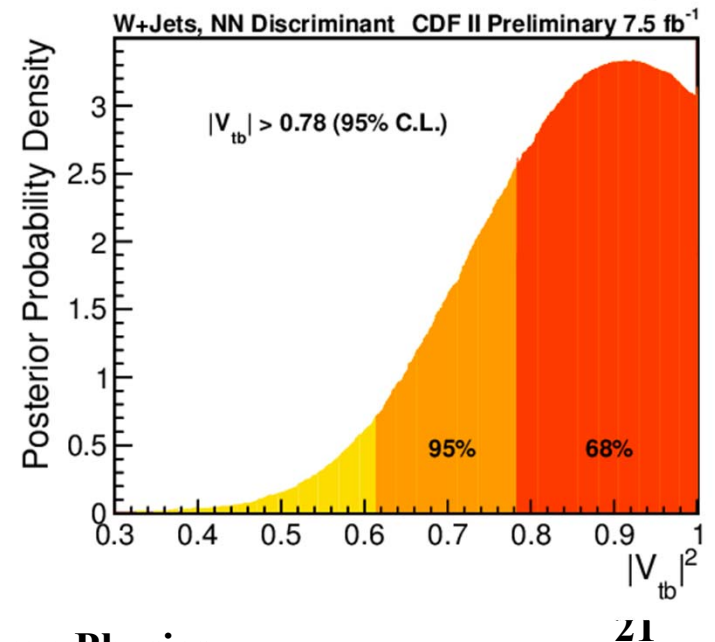
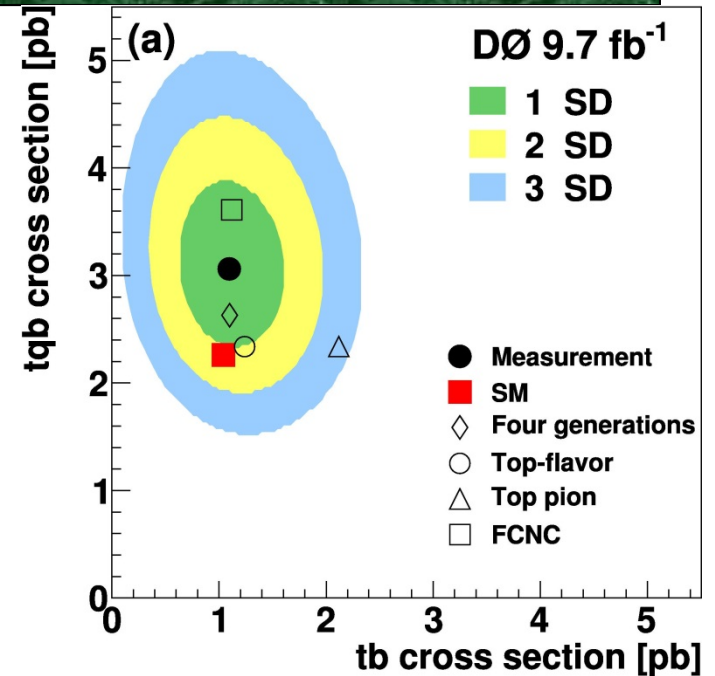
- **CDF Combination now complete in all channels**
 - Public Note 11080
- **Tevatron Combination**
 - arXiv:1305.3939
- **Strong impact on World combination**
 - arXiv:1403.4427
- **New DZero results in lepton+jets**
 - Very small uncertainties:
 $M_{\text{top}} = 174.98 \pm 0.76$
 - arXiv:1405.1756

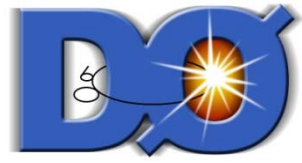




Single Top $s+t$

- **CDF Results in Met+Jets and Lep+Jets**
 - Public Notes 10793 and 10926
 - Combined results coming soon
- **DZero Result**
 - Phys. Lett. B 726, 656 (2013)
- **Tevatron Combination is well underway, results expected soon**





Observation of Single Top in the S-Channel

- **Single top production in the S-only Channel has now been observed**
 - Combination complete
 - PRL 112, 231802 (2014)
- **Observed significance 6.3σ**

s-channel single top quark, Tevatron Run II, $L_{\text{int}} \leq 9.7 \text{ fb}^{-1}$

Measurement

Cross section [pb]

CDF $l+jets$

$1.41^{+0.44}_{-0.41}$

CDF \cancel{e}_T+jets

$1.12^{+0.61}_{-0.57}$

CDF combined

$1.36^{+0.37}_{-0.32}$

D0 $l+jets$

$1.10^{+0.33}_{-0.31}$

Tevatron combined

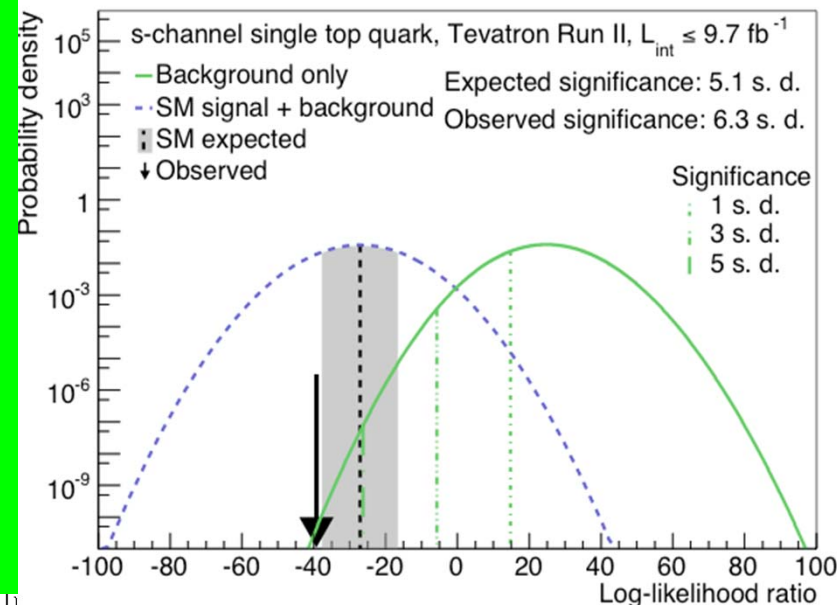
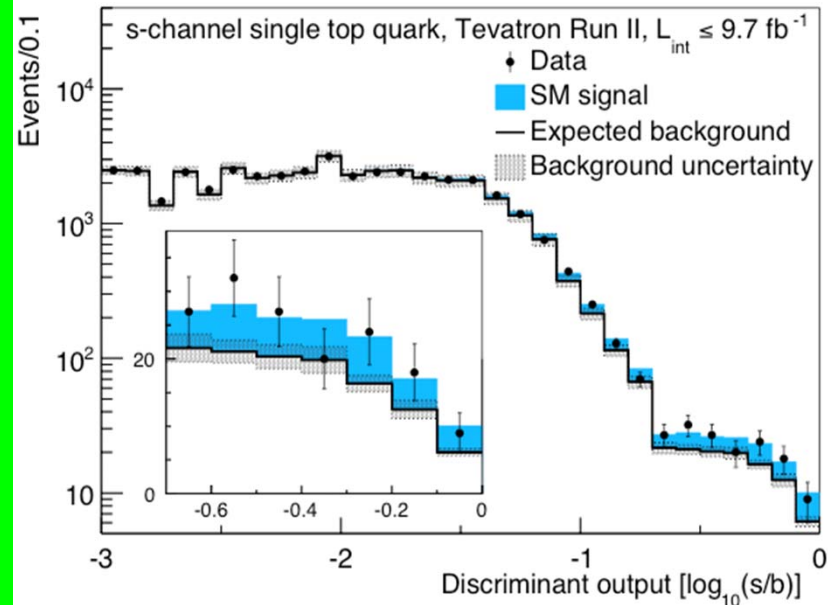
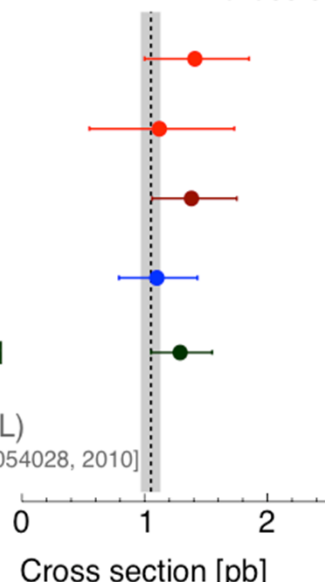
$1.29^{+0.26}_{-0.24}$

Theory (NLO+NNLL)

$1.05 \pm 0.06 \text{ pb}$ [PRD 81, 054028, 2010]

$m_{\text{top}} = 172.5 \text{ GeV}$

Cross section [pb]

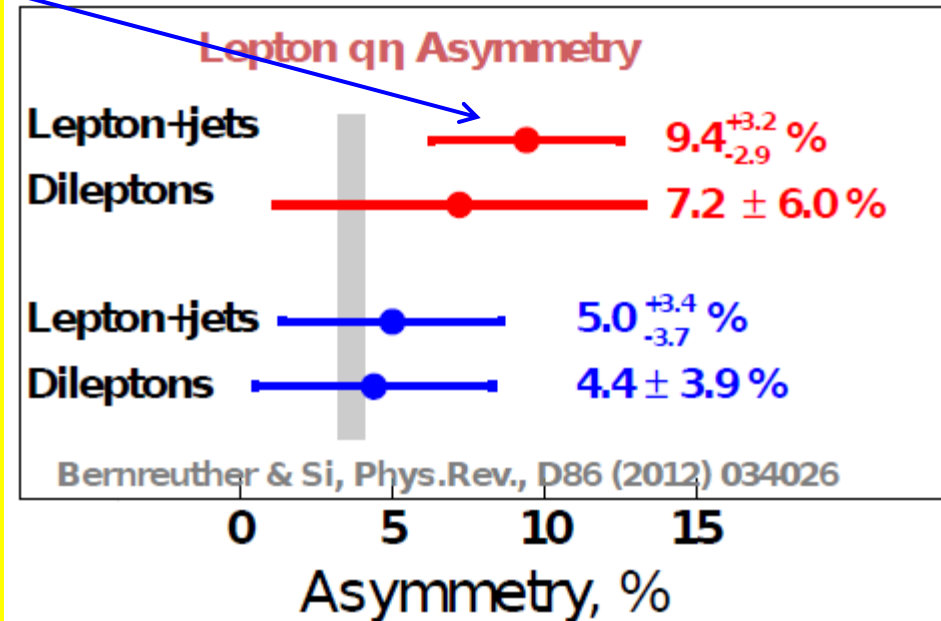
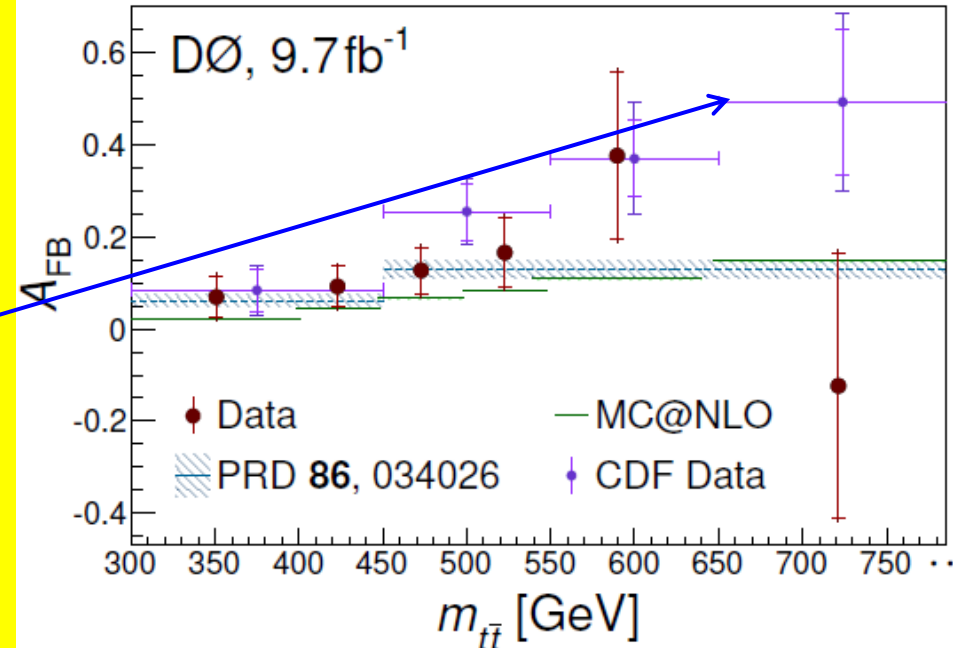




Forward-Backward Asymmetry in $t\bar{t}$



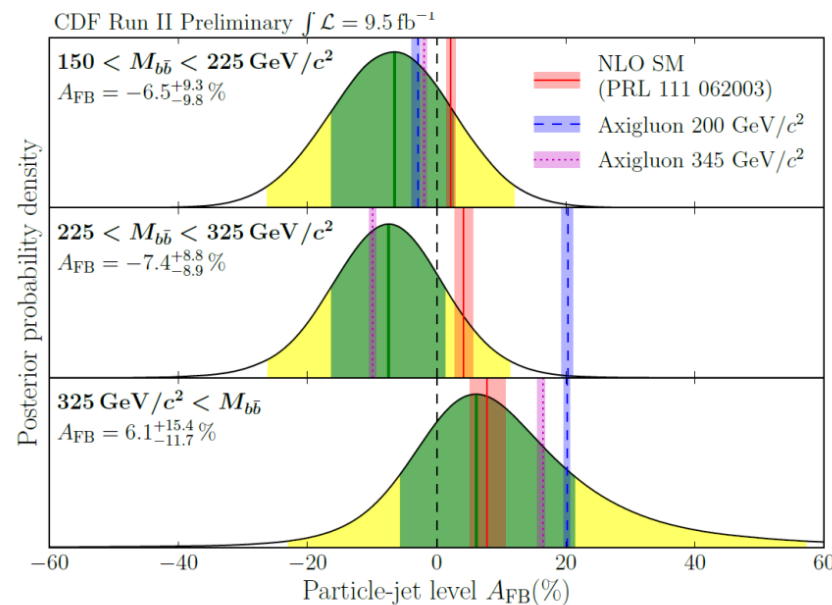
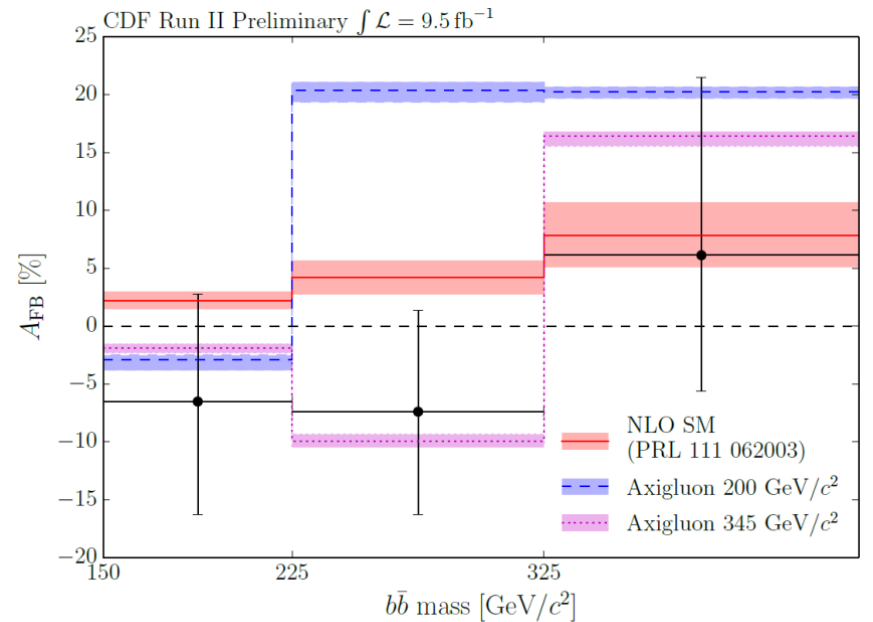
- **Hot topic for a number of years**
- **CDF Lep+Jets results shows anomalies**
 - In total reconstructed asymmetry
 - CDF: PRD 87, 092002(2013)
 - Most pronounced as a function of mass
 - In $d\sigma/d\cos\theta_t$ in l+jets
 - CDF: PRD 88, 072003(2013)
 - In lepton asymmetry
 - CDF: PRL 111, 182002(2013)
- Full suite of CDF and DZero results since in then
 - Leptonic: l+jets & dileptons
 - Full Reconstruction: Lep+Jets only
- Recent results from CDF and DZero are more consistent with SM
 - DZero leptonic Asy: PRD 88, 112002 (2013)
 - DZero Reconstructed: arXiv:1403.1294
 - CDF leptonic Asym: arXiv:1404.3698
- **Not sure what the final conclusion is: working to finish results, reconcile them all and combine**

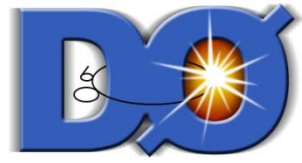




A_{FB} in High Mass $b\bar{b}$

- The A_{FB} in $t\bar{t}$ suggests that looking in the lower mass $b\bar{b}$ state is useful at large $b\bar{b}$ invariant masses
- New results consistent with SM
 - CDF Public note 11092
- DZero and CDF low mass results in the works





Future Publication Plans

CDF

- Expect ~30 papers in 2014
- Expect ~15 in 2015

DZero:

- Expect ~25 papers in 2014
- Expect ~15 papers in 2015

CDF

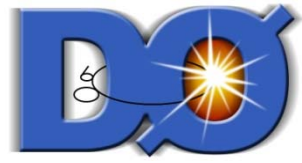
Topic	2014	2015
BSM	3	3
Higgs	1	0
Top	11	2
SM (EWK+QCD)	8	6
Heavy Flavor	6	4
Combinations	4	3
Total	34	18

DZero

Topic	By summer 2014	Beyond summer 2014
EWK	4	5
Higgs	1	1
Top	3	5
QCD	3	5
Heavy Flavor	2	3
Combinations	3	4
NIM	-	1
Total	16	24

Texas A

Perimeter Users Meeting -



Conclusions

- **The CDF and DZero collaborations are still doing exciting physics and publishing at a strong rate**
- **The Tevatron has now published over 1,000 papers and graduated over 1,000 PhD students**
- **The last year(s) have had many successes by focusing on legacy results that are competitive and complementary to the LHC**
 - **Single Top, W Mass, Top Mass, A_{FB} in tt, Higgs(bb)**
- **Modest support from the laboratory and funding agencies around the world is well leveraged and will assure many more important results to come based on the Tevatron data**
- **In the next year or so we expect many exciting results including the final Tevatron word on the Higgs Spin-parity in VHiggs(bb) Top mass, A_{FB} in tt and bb, W charge asymmetry and a W Mass measurement in the 10-15 MeV range**